

A review on solar energy use in industries

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ABSTRACT

Presently, solar energy conversion is widely used to generate heat and produce electricity. A comparative study on the world energy consumption released by International Energy Agency (IEA) shows that in 2050, solar array installations will supply around 45% of energy demand in the world. It was found that solar thermal is getting remarkable popularity in industrial applications. Solar thermal is an alternative to generate electricity, process chemicals or even space heating. It can be used in food, non-metallic, textile, building, chemical or even business related industries. On the other hand, solar electricity is widely applied in telecommunication, agricultural, water desalination and building industry to operate lights, pumps, engines, fans, refrigerators and water heaters.

It is very important to apply solar energy for a wide variety of applications and provide energy solutions by modifying the energy proportion, improving energy stability, increasing energy sustainability, conversion reduction and hence enhance the system efficiency. The present work aimed to study the solar energy systems utilization in industrial applications and looked into the industrial applications which are more compatible to be integrated with solar energy systems.

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Contents

1. Introduction	1777
2. Integration of solar energy into industrial systems	1779
3. Solar thermal energy	1779
4. Thermal energy for industrial processes	1780
4.1. Solar water heating (SWH)	1781
4.2. Steam generation using solar systems	1782
4.3. Solar drying and dehydration systems	1783
4.4. Solar refrigeration and air-conditioning systems	1784
4.5. Summary of solar thermal applications	1785
4.6. Solar thermal in food industry	1785
4.6.1. Solar thermal in building industry	1785
5. Photovoltaic (PV) systems	1786
5.1. Building-integration photovoltaic (BIPV) systems	1787
5.2. Solar electricity for industrial applications	1787
5.3. Solar powered water desalination industry	1788
6. Conclusions	1789
References	1789

1. Introduction

Energy use has become a crucial concern in the last decades because of rapid increase in energy demand. Moreover, environ-

mental issues of conventional energy resources such as climate change and global warming are continuously forcing us for alternative sources of energy. According to the statistics released by World Health Organization (WHO), direct and indirect effects of climate change leads to the death of 160,000 people per year and the rate is estimated to be doubled by 2020. Climate change causes natural disasters such as floods, droughts, and remarkable changes in atmosphere temperature. Moreover, some diseases become epidemic

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Nomenclature

WHO	World health organization
PTC	Parabolic trough collector
SWH	Solar water heater
PV	Photovoltaic
GPS	Geographical position system
RO	Reverse osmosis
MSF	Multi stage flash
MEB	Multi effect building
VC	Vapor compression
ER-RO	Reverse osmosis with energy recovery
ED	Electro dialysis

Table 1

Global industrial energy consumption pattern by fuel in 2006 and 2030 (%) [5].

Sources of energy	2006	2030
Liquids	34.6	28.6
Natural gas	24.1	25.6
Coal	24.8	24.3
Electricity	14.9	19.7
Renewable	1.5	1.8

Table 2

Industrial sector energy uses for selected countries [5].

Country	Industrial sector energy use (%)
China	70
Malaysia	48
Turkey	35
USA	33

among the societies mainly malaria, malnutrition and diarrhea. One of the disasters was reported in 2003 which attacked European countries and caused death of 20 thousand people while remained \$10 billion losses in agricultural sector [1].

Currently, conventional energy sources constitute almost 80% of global energy consumption. The urgent need to substitute the energy sources was postponed aligned with discovering nuclear energy in the middle of 20th century, which would stand out for ten to twenty times more than fossil fuels. However, there are some limitations associated with nuclear source of energy. For instance nuclear fusion is exposed of uranium and thorium ores which are considered fossil fuels as well. In addition, nuclear plants are currently available only in large scale power generations. Therefore, for cooking, heating and small scale applications renewable energy is still the best choice. It is the source of energy that mankind can continue their survival on the earth without depending on fossil fuels [2]. Renewable energy sources like solar, wind, biomass, hydropower and tidal energy are promising CO₂ free alternatives [3,4]. Despite the general awareness of advantages of renewable energy utilization, this source of energy contributed only about 1.5% of world energy demand in 2006. The trend is estimated to rise up to 1.8% in 2030. Table 1 shows global industrial energy consumption patterns for various sources of energy for the years 2006 and 2030.

The importance of energy in industrial development is very crucial since major fraction of energy is used in industrial processes. It has dominated more than 50% of total energy consumption worldwide. The delivered energy in industrial sector is utilized in 4 major sectors: construction, agriculture, mining and manufacturing. Industrial sector energy consumption, savings and emission

analysis for electrical motors, compressed air, and boilers have been discussed in [6–12] and revealed that a major chunk of energy is used in this sector. Table 2 shows the industrial sector energy use for few selected countries around the world.

Fig. 1 shows the industrial energy consumption trend until 2030.

Due to rapid growth in conventional fuel prices and environmental constraints, enterprises are not attracted to use fossil fuels in industrial sector anymore. By applying renewable energy based systems in industries, the greenhouse emissions could be reduced significantly. Therefore, traditional energy supplies should be shifted to renewable sources of energy and new technologies has to be developed and applied in industries.

Among all the renewable energy sources, solar power attracted more attentions as a greatest promising option to be applied in industries. Solar energy is abundance, free and clean which does not make any noise or any kind of pollution to the environment. So far, many attempts have been made to extract solar energy by means of solar collectors, sun trackers and giant mirrors in order to utilize it for industrial purposes. Solar energy applications in industry are divided into 2 main categories: the solar thermal and the photovoltaic. Some of the most common applications are hot water, steam, drying and dehydration processes, preheating, concentration, pasteurization, sterilization, washing, cleaning, chemical reactions, industrial space heating, food, plastic, building, textile industry and even business concerns [1], [2].

Table 3 shows the share of different sources of renewable energy for industrial applications (excluding hydroelectric and biomass) in term of annual production and global demand for 2001.

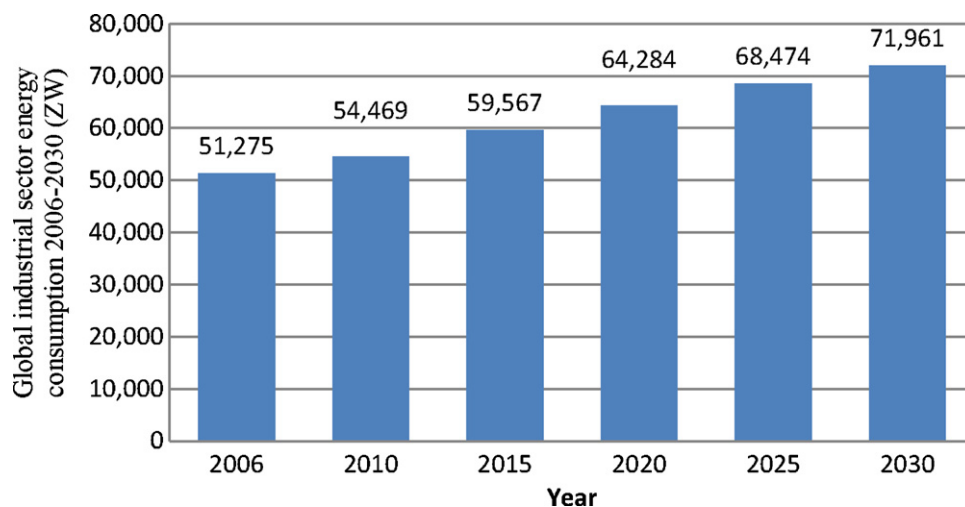


Fig. 1. Global industrial sector energy consumption during 2006–2030 [5].

Table 3
Renewable energy sources, annual production and global demand in 2001 [13].

Renewable source	Annual production (TJ)	% Global demand
Solar thermal	228720	0.523
Solar thermal (electric)	1200	0.003
Photovoltaic	630	0.001
Geothermal	128060	0.292
Geothermal (electric)	151390	0.345
Wind	35760	0.082
Tidal	2160	0.005
Total	547920	0.806

Due to the global energy shortage and controlling harmful environmental impacts, application of solar energy has receiving much attention in the engineering sciences. Hence, intense search for effective and economic methods to capture, store and convert solar energy into useful energy should not be neglected [2]. In the literatures there is no comprehensive review on the applications of solar energy in industrial facilities. It is expected that this review will be very useful for industrial energy users, policy makers, research and development organizations, and environmental organizations.

2. Integration of solar energy into industrial systems

A typical industrial energy system is composed of 4 main parts; power supply, production plant, energy recovery and cooling systems. Fig. 2 shows a block diagram of a typical industrial energy system.

The power supply provides the energy needed for the system to operate mainly from electrical energy, heat, gas, steam or coal. Production plant is the part of the system that executes proceedings of production. Energy is utilized in this part for running subsystems, pressure/vacuum/temperature solenoids, valves and switches. Solar energy systems can either be applied as the power supply sector or directly to a process. Table 4 has tabulated the solar energy applications and the technologies adopted in industrial processes.

3. Solar thermal energy

It can be stated that solar thermal is the conversion of solar irradiation into heat. Among renewable energy systems, solar thermal is considered as the most economical alternative. Typically, the systems use solar collectors and concentrators to gather solar radiation, store it and use for heating air or water in domestic, commercial or industrial plants. Fig. 3 presents a schematic diagram of solar irradiation conversion to mechanical energy [14].

Table 4
Solar energy applications, system technologies and type of systems commonly used in industry [14].

Solar energy application	Solar system technology	Type of system
SWH	Thermo syphon systems	Passive
	Integrated collector storage	Passive
	Direct circulation	Active
	Indirect water heating systems	Active
	Air systems	Active
Space heating and cooling	Space heating and service hot water	Active
	Air systems	Active
	Water systems	Active
	Heat pump systems	Active
	Absorption systems	Active
	Adsorption (desiccant) cooling	Active
	Mechanical systems	Active
Solar refrigeration	Adsorption units	Active
	Absorption units	Active
Industrial heat demand process	Industrial air and water systems	Active
	Steam generation systems	Active
Solar desalination	Solar stills	Passive
	Multistage flash (MSF)	Active
	Multiple effect boiling (MEB)	Active
	Vapor compression (VC)	Active
		Active
Solar thermal power systems	Parabolic trough collector systems	Active
	Parabolic tower systems	Active
	Parabolic dish systems	Active
	Solar furnaces	Active
	Solar chemistry systems	Active
		Active

The location, type of collector, working fluid to determine required storage volume, size of the system and storage volume to determine the heat exchanger size and the load are the factors that need to be considered for the specific applications [15].

However, it has to be noted for some applications that solar energy is not available continuously for 24 h. In such cases, addition supplementary measures should be provided to accumulate solar irradiation during sunny days, store it in an embedded phase transition and release it in a controlled manner in severe conditions.

To increase the efficiency of solar thermal systems, solar collectors are applied to heat the air or water as the medium of heat transfer. However, each collector is dedicated for a specific application. For example, flat-plate collectors are properly designed to be used in low temperature applications, the concentrating and sun-tracking parabolic trough collectors (PTC) are

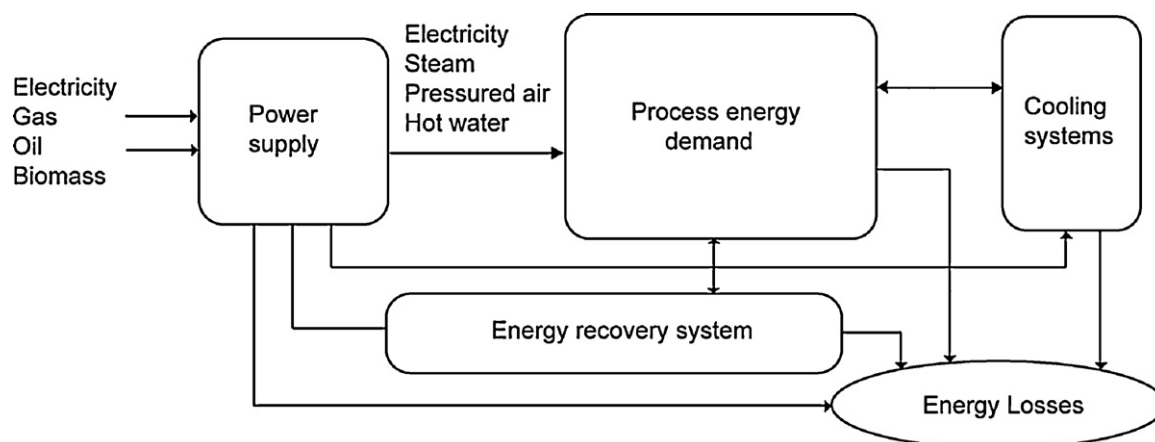


Fig. 2. Block diagram of a typical industrial energy system [3].

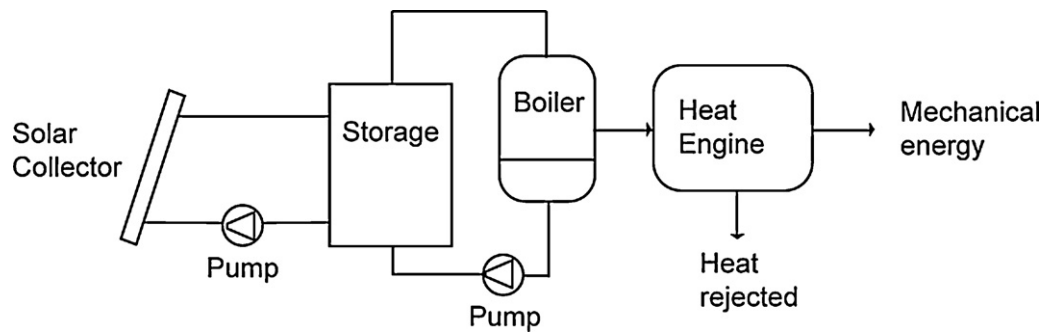


Fig. 3. Schematic of a solar-thermal conversion system [14].

Table 5
Types of solar energy collectors [15].

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Fresnel lens collector (FLC)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

suitable for high temperature applications in which the system can obtain temperature higher than 250 °C with high efficiency, two axes tracking collectors are applied in power generation, stationary (non-tracking) and one axis PTCs are mainly used in industrial heat processes. Among the collectors, movable collectors require higher maintenance cost compared to other collectors. Table 5 illustrates the three main categories and types of solar collectors currently used [15]. A concentration ratio, defined as the aperture area divided by the receiver/absorber area of the collector of each type is presented as well.

Cost of the energy generated by solar thermal systems varies from 0.015 to 0.028 C£/kWh depending on initial investment and the type of solar collectors used [15]. Large scale solar thermal systems with large collector fields are more economical. They need less initial investment compared to several small plants; however, the collector cost is higher.

4. Thermal energy for industrial processes

Nearly all the industrial energy networks and systems are partially or fully dependent on burning fossil fuels to generate essential thermal energy. Distribution of energy consumption indicated that about 13% of thermal industrial applications require low temperatures thermal energy up to 100 °C, 27% up to 200 °C [16] and the remaining applications need high temperature in steel, glass and ceramic industry [3]. Table 6 shows few of potential industrial processes and the required temperatures for their operations.

Many industrial processes are involved in heat utilization with temperature between 80 °C and 240 °C [17,18]. Industrial energy analysis shows that solar thermal energy has enormous applications in low (i.e. 20–200 °C), medium and medium-high (i.e. 80–240 °C) temperature levels [15]. Almost all industrial processes require heat in some parts of their processes. In southern European countries, almost 15% of the final energy demand in industrial sector is used for heating applications [19]. Most common applications for solar thermal energy used in industry are the

SWHs, solar dryers, space heating and cooling systems and water desalination.

Solar as an input power is widely used for heat engines in many industrial applications. Stirling engines use any kind of external heat source for their operation. They are highly reliable, simple in design and construction, easy to operate and cost effective. Nevertheless, the efficiencies of such mechanical devices are quite low. Compared to external combustion engines, they perform more efficiently with less exhaust emissions. Using solar irradiation to generate heat for Stirling engines can reduce the cost and complexity of the system while increasing their efficiency. Mass production of solar powered Stirling engines would make them cost effective. Generating solar electricity using Stirling engines in the range of 1–100 kW for industrial applications is the cheapest alternative [19].

Stirling engines use compressed fluids like air, hydrogen, helium, nitrogen or steam on a Stirling cycle. Stirling engines are applicable in numerous applications where quite operation is required or in systems with multi-fueled characteristics, very good cooling source, low speed, constant power output and low pace of changing output power [19].

Using solar energy to generate thermal energy for industrial processes not only reduces dependency on fossil fuel resources but also minimizes greenhouse emissions such as CO₂, SO₂, NO_x [3]. Nevertheless, there are some challenges for merging solar heat into a wide variety of industrial processes like periodic, dilute and variable nature of solar radiation [3]. Solar thermal applications in industrial sectors are classified as below:

1. Hot water or steam demand processes
2. Drying and dehydration processes
3. Preheating
4. Concentration
5. Pasteurization, sterilization
6. Washing, cleaning
7. Chemical reactions

Table 6
Heat demand industries and ranges of temperatures [15].

Industry	Process	Temperature (°C)
Dairy	Pressurization	60–80
	Sterilization	100–120
	Drying	120–180
	Concentrates	60–80
	Boiler feed water	60–90
Tinned food	Sterilization	110–120
	Pasteurization	60–80
	Cooking	60–90
	Bleaching	60–90
Textile	Bleaching, dyeing	60–90
	Drying, degreasing	100–130
	Dyeing	70–90
	Fixing	160–180
	Pressing	80–100
Paper	Cooking, drying	60–80
	Boiler feed water	60–90
	Bleaching	130–150
Chemical	Soaps	200–260
	Synthetic rubber	150–200
	Processing heat	120–180
	Pre-heating water	60–90
Meat	Washing, sterilization	60–90
	Cooking	90–100
Beverages	Washing, sterilization	60–80
	Pasteurization	60–70
Flours and by-products	Sterilization	60–80
Timber by-products	Thermo diffusion beams	80–100
	Drying	60–100
	Pre-heating water	60–90
	Preparation pulp	120–170
Bricks and blocks	Curing	60–140
Plastics	Preparation	120–140
	Distillation	140–150
	Separation	200–220
	Extension	140–160
	Drying	180–200
	Blending	120–140

8. Industrial space heating
9. Textile
10. Food
11. Buildings
12. Chemistry
13. Plastic
14. Business establishments

4.1. Solar water heating (SWH)

Solar water heating industry constitutes the majority of solar thermal applications in both domestic and industrial sectors. They are considered as the most cost-effective alternatives among all the solar thermal technologies currently available. SWH systems are now in commercialized stage and very mature in many countries in the world. Since 1980, utilization of SWHs has been increased with 30% annual growth rate [21], [22].

SWHs are usually composed of solar collectors and a storage space. It works on the basis of the density inequality of hot and cold water or thermo syphon. In colder countries, integrated collector/storage SWHs is more common because of simple and compact structure. Batch solar collectors are more suitable for compensating sun radiation limitations in the evening and afternoon [1,21]. A schematic of a flat plate solar water heating system is shown in Fig. 4.

Fig. 4 is the block diagram of SWH systems commonly used in industrial applications in which the water never go back to the storage tank. It involves solar collectors, circulating pump, load pump, storage space or tank, differential thermostat and thermal relief-valve. The controller components are required to adjust temperature for the system operation. If the temperature of the tank goes above the pre-set value, the valves will release energy by mixing the hot water with main water supply system and obtain required temperature. An auxiliary heater is considered for the situations that temperature of the tank is not adequate.

SWHs are generally divided into 2 main groups: the once-through systems and the recirculating water heaters. Once-through technologies are largely used in cleaning procedures of food industry. Therefore, the used water is not allowed to circulate again in the system due to contaminants available in the used water. The recirculating water heaters are exactly similar to domestic SWHs [14].

Industrial heat demand applications usually use hot water (low-pressure steam) or pressurized steam corresponding to the heat required for the system operation. Water is usually the running fluid in thermal applications depending on its availability, thermal capacity, storage convenience and low cost. Nevertheless, cost of the storage system increases remarkably when higher pressure is required. For temperatures above 100 °C, the system is needed to be pressurized. For medium temperature (above 100 °C) applications, mineral oils are used. However, higher costs, tendency of cracking and oxidation are few issues involved in such systems [20]. SWHs are applied in medium temperature hot water applications are as follows:

- Water preheating to be used in cleaning, washing and dyeing
- Steam generating
- Direct integration to a conventional system

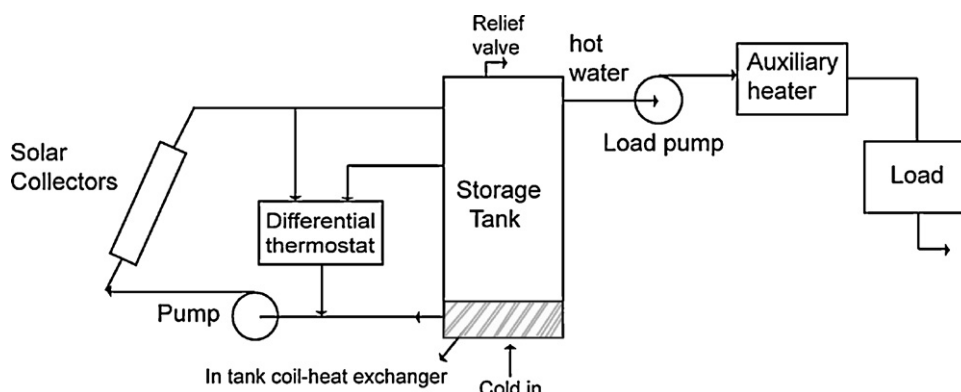


Fig. 4. Block diagram of a SWH system [20].

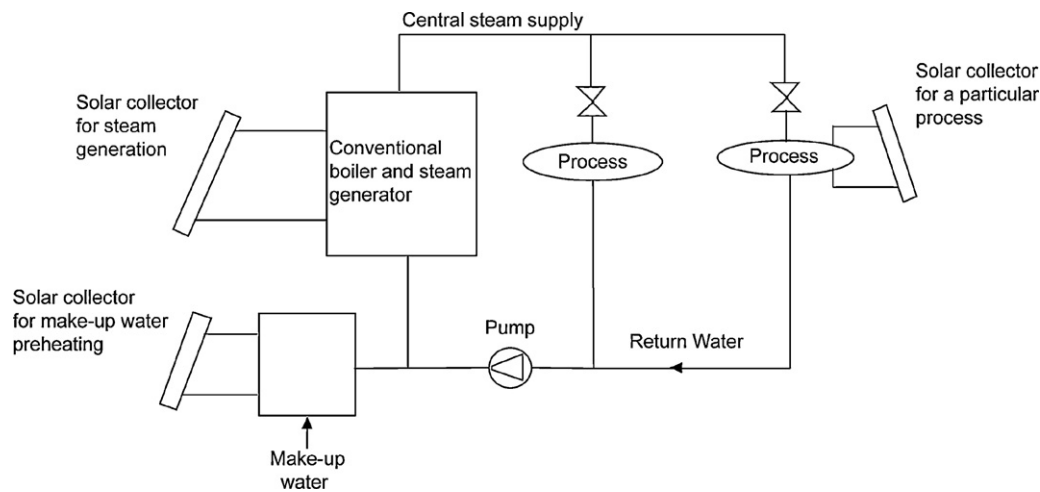


Fig. 5. Integration of solar collectors to an industrial thermal powered system [15].

Fig. 5 shows the integration of solar collectors to an industrial thermal powered system.

Processes which require water preheating have met higher efficiencies because of the nature of solar systems that input temperature is slightly low. The main reason is that in such systems simple collectors capture the sunlight at the temperature required for the load.

Solar thermal is also used in textile industry for heating water at temperatures close to 100°C for bleaching, dyeing and washing purposes [15]. Currently, fossil fuels are used for fuel-run in textile industry. Therefore SWHs can significantly contribute to reduce the ecological problems associated with textile industry. Built-in-storage water heaters are introduced in Pakistani textile industry to further improve the performance and stability of the systems [1].

Another emerging SWH's market which is already widespread and reached developmental stage is building industry. Statistics shows that SWHs and space heating and cooling is going to be generalized and will achieve 20–30% of the full commercialization [20]. Most of the developing countries are located in warm climate and hence hot water is not as important as in developed countries which are situated in colder climate. However, according to [21], nearly 10 million SWHs are presently installed in developing countries.

By 2000, the total area of $500,000\text{ m}^2$ was covered by solar collector installations in India. By 2001, millions of Chinese households were equipped with SWH. Egypt and Turkey are using SWHs in hundreds of thousands of households. Botswana and Zimbabwe have installed 15,000 and 4000 SWHs, respectively. Thailand has captured 15% of SWH market worldwide. Furthermore, SWH market is available in Zimbabwe, Namibia, South Africa, Botswana, Morocco, Tunisia, Papua New Guinea, Kenya, Tanzania, Lesotho and Mauritius. In Africa, the payback period for a small scale SWH is as short as 3–5 years [21,23].

On the other hand, large scale SWHs has significant economical benefits. For example, in Nepal monthly electricity bill was reduced by 1200 Euro by installing SWHs in a school for 850 students. Even after 20 years 75% of collectors are still operating properly. Another advantage of installing such project is to encourage domestic sector to use the new technology for kitchen, bath and swimming pool with temperature between 45°C and 50°C .

Designers, engineers, architectures, service engineers and material providers may play critical roles in sustainable development for the large scale production. Besides, various policies by governments and communities might have a great influence to encourage domestic and industrial sector to apply the new technology [22].

4.2. Steam generation using solar systems

Low temperature steam is extensively used in sterilization processes and desalination evaporator supplies. Parabolic trough collectors (PTCs) are high efficient collectors commonly used in high temperature applications to generate steam. PTCs use 3 concepts to generate steam [24]; the steam-flash, the direct or in situ and the unfired-boiler. In the steam-flash method, pressurized hot water is flashed in a separate vessel to generate steam. In an in situ method, there are 2 phase flow in the collector receiver to generate steam. In an unfired-boiler system, steam is generated via heat-exchange in an unfired boiler. In this concept, a heat medium fluid goes through the collector. Fig. 6 is a schematic of a steam-flash system. The system pressurized the water to avoid boiling. The pressurized water goes through the solar collector and eventually flashed to a flash vessel. Water level in flash vessel is maintained at constant level through feed water supply.

Fig. 7 shows the direct or in situ boiling concept. The only difference is that flash-valve is removed in this configuration. Make up water is directly heated to generate the steam in the receiver.

Fig. 8 illustrates the unfired boiler system. This system is rather simple than before mentioned systems. The pressure is quite low and control scheme is straightforward.

Flash-steam and direct-steam systems require approximately the same initial cost [25]. However, in situ systems suffer from stability problems [26] and scaling of the receivers. To design an appropriate industrial application, the proper steam generation system with suitable decisive factors should be chosen.

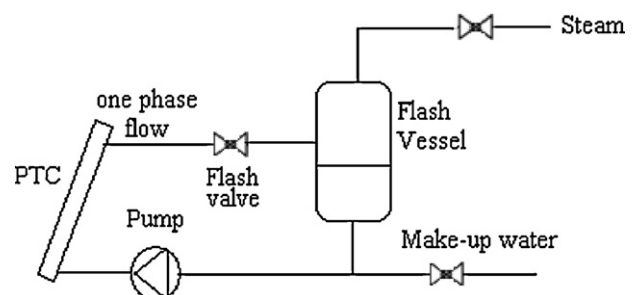


Fig. 6. The steam-flash generation system [14].

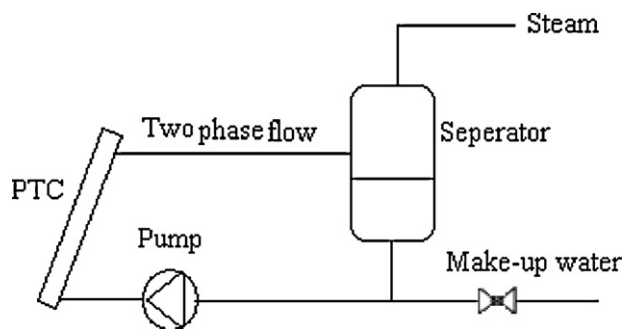


Fig. 7. The in situ generation system.

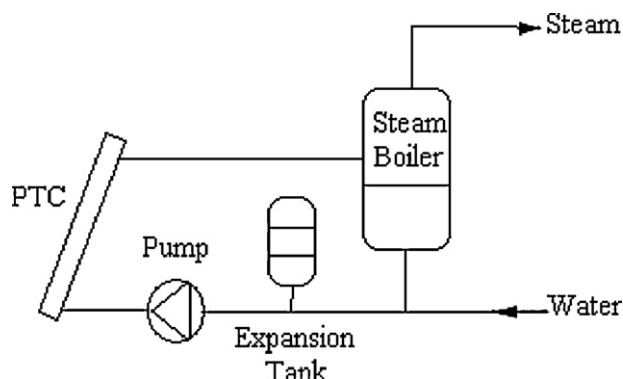


Fig. 8. The unfired-boiler steam generation concept.

4.3. Solar drying and dehydration systems

Solar drying and dehydration systems use solar irradiance either as the solely power supply to heat the air or as a supplementary energy source. Conventional drying systems burn fossil fuels for their performance while the solar dryers take advantage of sun irradiation for drying and dehydration processes in industries such as bricks, plants, fruits, coffee, wood, textiles, leather, green malt and sewage sludge [3].

They are categorized into 2 main groups: high and low temperature dryers. Almost all high temperature dryers are currently heated by fossil fuels or electricity but low temperature dryers can use either fossil fuels or solar energy. Low temperature solar thermal energy is ideal for use in preheating processes as well [27].

On the other hand, solar dryers are also classified based on the method of air flow generation into 2 major groups: natural-circulation (passive) and forced-convection (active) solar dryers.

Generally, passive solar dryers use solar energy which is abundantly available in the environment. Therefore, this technique has been usually addressed as the only commercially available method

in agriculture industry in developing countries. They are categorized into 2 main methods; open to sun and natural-circulation solar-energy crop drying method. Developing countries especially who are in tropical climate are widely taking advantage of open-to-sun passive drying systems. They dry the crops using 2 main approaches; in the field or in situ and by spreading it on the ground or any vertical or horizontal plate exposing to solar radiation.

Open to sun passive dryers are very common since they have low initial and running cost and less maintenance required. However, open-to-sun drying method produces huge wastes and crop losses due to imperfect drying, fungus and insect infestation, birds and rodent encroachment. In addition, unpredictable changes in weather and climate changes such as rain and even cloudiness affect the efficiency of such systems.

Natural-circulation dryers are another type of passive solar dryers which are favorable options for rural and isolated areas. In this type of dryer, the heated air flow toward the drying crops on the basis of buoyancy forces or using wind pressure or even a combination of both. They offer many advantages over open-to-sun drying systems:

- Require smaller area of land for similar quantities of crops
- High efficiency due to more protection against fungus, pets and rodents
- Shorter time is needed
- Protection against unpredictable rains
- Low capital and maintenance cost
- Commercially available

Active solar drying systems use solar energy in combination with electricity or fossil-fuels to generate power for pumps and engines to provide air circulation. In this type of solar dryer, solar energy is the only source to generate heat. This method is used in large-scale commercial drying applications. Such a system can reduce the energy consumption along with controlling the drying conditions.

High temperature solar heaters are used for direct drying process. However, for medium and low temperature systems, the fossil-fuel fired dehydrator is applied to boost the air flow temperature to the necessary point. The latter system is called “hybrid solar dryer”. It avoids the effects of fluctuating energy output from the solar collector at night or when the sun irradiation is low. Solar active dryers are widely used in high temperature drying processes where continuous air flow is required [28–30].

Based on system component arrangements and the way system uses solar heat; both active and passive solar dryers could be classified into 3 main groups: integral type, distributed type and mixed mode dryers [31]. Table 7 shows the working characteristics of integral and distributed methods of natural-circulation solar dryers.

Table 7
Working principles of integral and distributed methods in natural-circulation solar dryers [27].

	Type of system	
	Integral	Distributed
Principal modes of heat transfer to crop	Direct absorption of solar radiation and convection from heated surrounding air	Convection from pre-heated air in an air-heating solar-energy collector
Components	Glazed drying chamber and chimney	Air-heating solar-energy collector, ducting, drying chamber and chimney
Initial cost	Low	High
Construction, operation and maintenance	Simplicity in both construction and operation. Requires little maintenance	Requires high capital investment in materials, large running costs More operational difficulties of loading and occasional stirring of the crop
Efficiency	Low efficiency due to its simplicity and less controllability of drying operations	High efficiency since individual components can be designed to optimal performance

Table 8
Classification of solar energy drying and dryer systems [27].

"Natural" or Open to sun drying	Crops dried in situ Post harvest drying		
Solar energy dryers	Active	Distributed type Mixed mode	
	Passive	Integral type	Cabinet dryer Green house dryer

Industries which involve drying process usually use hot air or gas with a temperature range between 140 °C and 220 °C. Solar thermal systems can be integrated with conventional energy supplies in an appropriate way to meet the system requirements. Heat storage seems to be necessary when system is required to work in the periods of day when there is no irradiation [15].

Solar dryers can extensively be used in food and agriculture industry to improve both quality and quantity of production while reducing the wastes and minimize environmental problems. In spite of using large scale solar dryers in commercial food industries, lack of information is the main barrier to further improve the technology in developing countries. This type of dryer has high initial investment and installation costs. Therefore, only large farms can afford the monetary burdens [23,32]. Table 8 shows the classification of solar energy drying and dryer systems.

4.4. Solar refrigeration and air-conditioning systems

Increasing standards for living and working conditions, remarkable rate of urbanization, unpleasant outdoor pollutions and affordable price of air-conditioners have initiated increasing demand for air conditioning systems. The more request for air conditioning, the more need for electrical power. Hence, power stations meet their peak load demand in hot summer days leading to blown-out situations [33]. Statistics indicate a huge rise in the number of air conditioning installations within European countries since last 20 years where the cooling capacity has been five-folded. Energy consumption of air conditioners was 6 TJ and 40 TJ in 1990 and 1996, respectively and it is rising to reach 160 TJ in 2010 [34]. Fig. 9 is the block diagram of a typical solar cooling system with refrigerant storage.

The peak demand in cooling loads is usually happening when the solar irradiation is high. Solar air conditioners are the type of solar energy application that fulfills this specific condition. They do not require Freon refrigerants or any other harmful substances that depletes ozone layer. Furthermore, operating costs are 15% less than conventional air conditioning systems. By installing solar assisted cooling systems in southern European and Mediterranean region, about 40–50% of primary energy was saved [36]. Fig. 10

illustrates the working principles of an absorption air conditioning system.

Solar powered air conditioners are usually connected to the heat supply cooling devices. They require solar collectors, heat buffer storage, heat and cold distribution systems, heat supply cooling devices, cold storage and an auxiliary (backup) heater. The auxiliary heater is connected parallel to the collector or the collector/storage, or integrated as an auxiliary cooling device. It can even be combined to the system in both arrangements, simultaneously [36].

Indoor air conditioning seems to be a necessity in commercial and residential buildings such as hotels with growing market in building industry worldwide. Traditional methods to generate electricity can be replaced with solar energy in heat-driven cooling technologies. The most cost effective ventilation system in a building is a system which is capable to provide both heating and cooling requirements [35].

Generally there are two different solar powered air conditioning systems: closed (recirculating) and open cycle systems. The closed-cycle system uses heat-driven pump which is supplied by solar energy. It requires solar collectors for its performance which increases the initial investment required for the system. It rejects heat from condenser and supply desorbers. The operations are performed in two distinct pressure and three temperature levels.

- Low temperature for cooling in the evaporator;
- Intermediate temperature in the absorber and condenser;
- High temperature in the desorber.

Closed-cycle systems are capable of being adopted with solar-powered installations with high temperature solar collectors. In addition, they can be applied in solar assisted air conditioning applications because of simplicity, wide range of heating temperatures and noiseless operation. Re-circulating air conditioning use a mixture of recycled air with ambient air in food crop industry and lumber.

In open cycle systems, solar energy is used to provide the appropriate temperature for heating the ambient or exhaust air and regenerate the sorbent. Open-cycle systems use dehumidifier to the process air before supplying to the conditioned space [36]. In open cycle systems, ambient air is heated where recirculating of air is not practical. The examples in drying applications include sup-

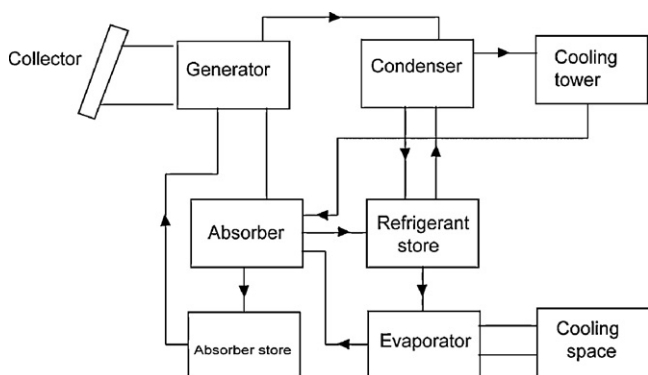


Fig. 9. Block diagram of a typical solar cooling system with refrigerant storage [35].

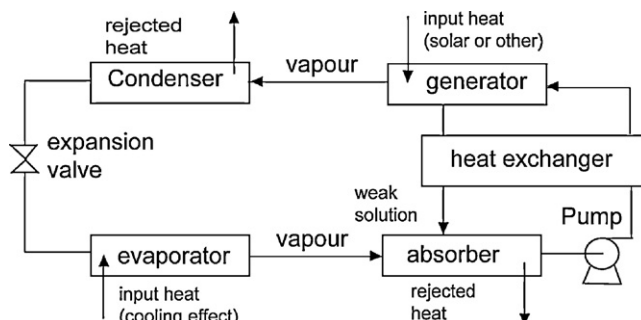


Fig. 10. Working fundamentals of an absorption air conditioning system [14].

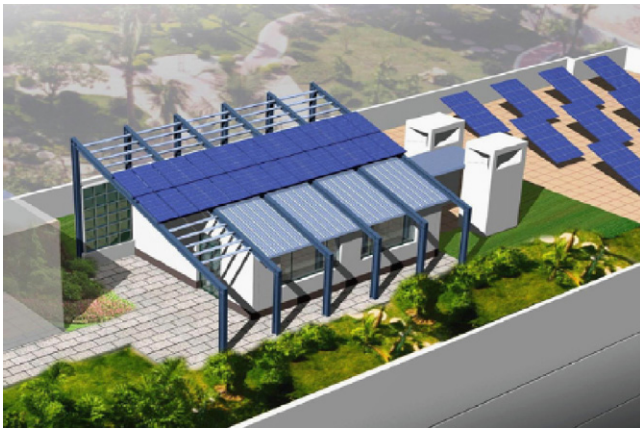


Fig. 11. Solar air conditioning system installed on the rooftop of a building [22].

plying fresh air to hospitals and paint spraying. Nevertheless, open cycle applications are highly efficient where recirculating systems can improve the quality of the product because of adequate control on drying rate [14].

Researches aimed toward environmental protection and improvements in components and performance of the solar powered air-conditioning systems. They reported that generator inlet temperature, collector choice and system arrangement are the factors need to be considered for design and operation of a system. Despite new revelation of heat-driven cooling technologies; numerous large-scale solar air conditioners exist in commercial stage in the market. They usually take advantage of sun collectors to satisfy capacities more than 40 kW. Many attempts and efforts have been put to develop this technology and many projects have been introduced to demonstrate solar powered buildings air conditioning systems. Governments and communities have demonstrated some projects to fascinate attentions to new solar air conditioners. However, there are few problematic issues such as high initial cost, lack of information and experience for designing, operating and running maintenance of the systems [36]. Fig. 11 shows an example of solar air conditioning system installed on the rooftop of a building located in China.

4.5. Summary of solar thermal applications

Solar thermal systems are widely used in industrial processes. However, the integration of each system into an industrial process has its own advantages and disadvantages. Table 9 presents a summary of the types of solar thermal system and techno-economic features of each system.

Two major industries that have further potential to apply solar thermal energy are explained as below.

4.6. Solar thermal in food industry

Food industry has favorable conditions to use solar heat since treatment and storage processes of food products are highly durable. Authors [37] conducted a study on non-concentrating solar collectors commonly used in food industry in Germany. The system analysis showed that efficiency of the system is comparable to SWHs and solar space heating systems. Solar thermal can be applied in milk, cooked meats (sausage and salami) and brewery industries at medium temperature for washing, cleaning, sterilizing, pasteurizing, drying, cooking, hydrolyzing, distillation, evaporation, extraction and polymerization.

In brewing industry, around 80% of overall final energy consumption is used in the form of thermal energy. This amount of

energy is dedicated for three main processes: boiling the wort (25–50%), washing the bottles (25–40%), and pasteurization. Solar thermal is used in malt factory for brewing processes as below:

- Low pressure steam generation at temperature 100–110 °C
- Wort refrigeration; using absorption cooling
- Malting process; for barley drying
- Stop germination of grains after germination
- Conservation with hot air at temperature 60–80 °C
- Air cooling in the germination process
- Power supplying of washing machines for returned bottles
- The wither and kiln processes

Food preservation industries also use solar heat in scalding, sterilization (vegetables, meat and fish), cleaning, pre-cooking, can sealing, cooling and refrigeration.

Dairy industries can also fully utilize solar energy for their various process operations. They usually operate for the whole week with no day off. Thus solar systems can be considered very cost effective in this type of industry. Dairy industries mainly use thermal energy for pasteurization (60–85 °C), sterilization (130–150 °C) processes and even for drying milk to produce powder. Milk powder industries are needed high constant energy with a large running time up to 8000 h/year [38]. Milk and whey are scattered in the spray-dryers at temperature range 120–180 °C.

Authors [39] introduced a case study for solar thermal applications in an energy intensive food industry in India. Sweet meat industry has both economical and traditional culture aspects of the country. The conventional systems are running with diesel fuels. Since they do not need high temperature for their performance, solar energy is a good substitute to supply energy for the system. Sweet meat industry is currently in commercial stage. It was reported that about 20% of annual production cost is spent just for annual energy consumption. It is recommended to use parabolic concentrators in sweetmeats production plants to maintain the quality and taste of the products [40].

4.6.1. Solar thermal in building industry

Building industry and the industries associated with it have dominated as the second largest energy users of the world energy consumption. In China, 27.8% of total energy demand is dedicated to the building sector [22] while energy expenditure in residential and commercial buildings stands for about 40% of Europe's energy budget [41].

Currently, solar energy is widely applied directly or indirectly in building industries. Using solar energy in building, industries can lead the communities to create immense environmental and economic benefits. Solar building industries are an inevitable move toward solar technology in the near future. Moreover, customary passive solar thermal systems are moving toward integration of solar material, substances and systems in buildings. Solar energy in building industries was limited in a few applications for several centuries. However, by developing solar technology, it is extensively used as SWHs, solar ventilation, air conditioning systems and photovoltaic power systems. Solar energy in building industries has three distinguished applications:

- Passive sunspace; the building collects and distributes sun radiation taking advantage of the building orientation, structure and materials.
- Active sunspace; the building applies solar heating system to generate heat or cool. The system is usually containing sun collectors, fans, pumps, radiators, solar air conditioners and absorption chillers.
- Photovoltaic applications; the building usually called “zero emission building” uses PV power system to generate electricity lightening, heating, ventilation and air cooling.

Table 9
Summary of solar thermal systems for the integration to industrial processes [3].

System	Cash ratio	Storage	Process control	Heat demand	Heat transfer medium	Type of collector
Direct heat transfer	Low	No	Continues	Always much higher than solar fraction	Air Water, process medium Steam	Air collectors Depending on temperature level of the process PTC
Indirect heat transfer	Low	No	Continues	Always much higher than solar fraction	Primary: water or water + glycol, thermo-oil Secondary: air, water, steam, process medium	Depending on temperature level of the process
Indirect heat transfer with storage	High	Yes	At intervals continues	The same or higher than solar fraction	Primary: water or water + glycol, thermo-oil Secondary: air, water, steam, process medium	Depending on temperature level of the process

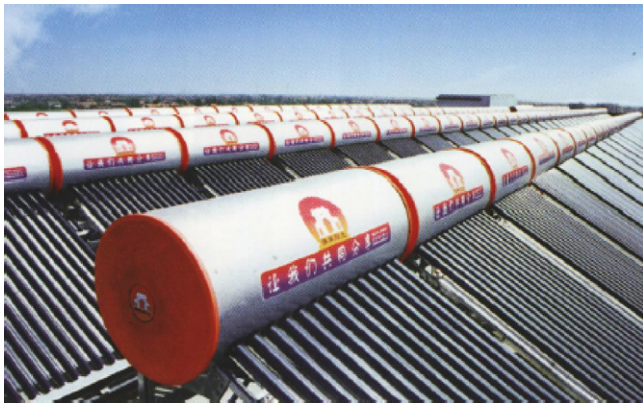


Fig. 12. SWH system installed on a rooftop [22].

Solar heating system for building industries consists of both passive and active technologies which are generally embedded in building materials and substances. Building industry uses solar heat directly to provide building heat demand using SWHs, trombe wall and solar roof. Absorbed heat by the solar collectors can be accumulated in materials with excessive heat capacity such as a liquid, air, packed bed, phase-change and heat-of-fusion units in the floor and wall materials for the periods when there is no sun present in the sky.

Solar space heaters are more complicated and need larger panels to collect sufficient sun radiation compared to SWHs. Fig. 12 shows a SWH system installed on a rooftop.

To make full utilization of solar sun in solar integrated buildings, the buildings usually should be south oriented. The glass windows and trombe walls collect the sunlight through the day and warm the buildings. In such buildings, appropriate ventilation seems to be necessary since the absorbed heat should be circulated in the building. Fig. 13 is a solar energy heating building of a demonstration project which uses trombe wall technology for natural ventilation. Use of solar heating systems in buildings found to be cost effective with long lifetime.

5. Photovoltaic (PV) systems

A solar cell converts energy in the photons of sunlight into electricity by means of the photoelectric phenomenon found in certain types of semiconductor materials such as silicon and selenium. Efficiency of solar cells depends on temperature, insolation, spectral characteristics of sunlight and so on. Presently, efficiency of photovoltaic cells is about 12–19% at the most promising conditions. Table 10 presents PV technology goals have been accomplished between 2000 and 2005.



Fig. 13. Solar energy heating building with trombe wall [22].

Photovoltaic systems are generally categorized into 2 main groups: stand-alone and grid connected systems [43,44]. Stand alone systems are the systems which are not connected to the grid and energy produced by the system is usually matched with the energy required by the load. They are usually supported by energy storage systems such as rechargeable batteries to provide electricity when there is no sunlight. Sometimes wind or hydro systems are supporting each other, where they are called “photovoltaic hybrid systems”. On the other hand, grid connected systems are the systems which are connected to the public grid. This kind of connection removes the dilemma by stand alone systems. They demand energy from grid when there is not enough power generation on the panels and feed in the power to the grid when there is more than required power by the system. This trend is a concept called “net metering”.

It is expected that grid connected systems are growing in the developed countries while the priority is given for the stand alone systems in developing and non-developed countries. Small PV power systems are widely used in building industries where they can generate electricity for lights, water pumps, TVs, refrigerators and water heaters. There are also some villages called “solar village” that all the houses are operated by solar energy system. Other commonly applications for stand-alone systems are:

Table 10
PV technology goals have been accomplished between 2000 and 2005 [42].

Parameters	1995	2000	2005
PV modules efficiency (%)	7–17	8–18	10–20
PV modules cost (\$/Wp)	7–15	5–12	2–8
System life (years)	10–20	>20	>25

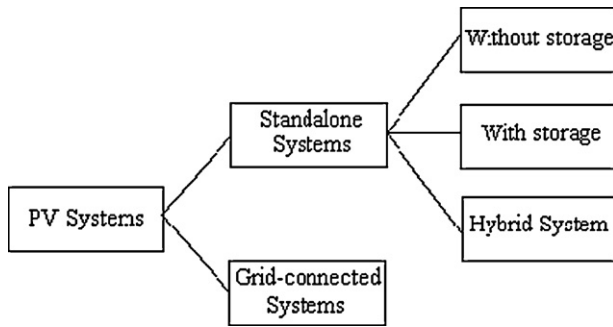


Fig. 14. Types of PV systems [43].

- Stand alone systems on solar cars, vans and boats,
- Remote cabins and homes,
- Parking ticket machines,
- Traffic lights,
- Applications in gardening and landscaping;
- Solar pump systems and desalination.

Stand alone systems seems to be necessary where there is no access to the public grid or where there is a huge cost of wiring and transferring electricity to the rural areas. The operation of standalone systems depend on the power extracted from the PV panels. Fig. 14 shows various types of the PV systems:

5.1. Building-integration photovoltaic (BIPV) systems

Building industries use solar energy not only for heating and cooling purposes in ventilation and air conditioning systems but also to generate electricity by photovoltaic cells. PV solar industries definitely can contribute to the world electricity demand. PV installation capacity in China was about 300 kW in 2005 and therefore total PV installation in the country was around 1 MW. The current total global PV installed capacity is about 3 GWp.

High capital investment and low efficiency have limited the applications of PV systems in building industries. However, PV panels have experienced 86% reduction in the cost while increasing in PV module production rate. The price for solar energy was around \$25/W in 1970 which has dropped to around \$3.50/W in recent years [45,46]. The PV cell productions in the world have increased from 10 MWp/yr in 1980 to 1200 MWp/yr in 2004. Fig. 15 shows the trend of PV module production between 1988 and 2003.

PV integrated buildings use photovoltaic cells replacing traditional building materials in the wall, rooftop, and balcony or even as semitransparent glass windows. Fig. 16 shows a typical BIPV system with shading materials.

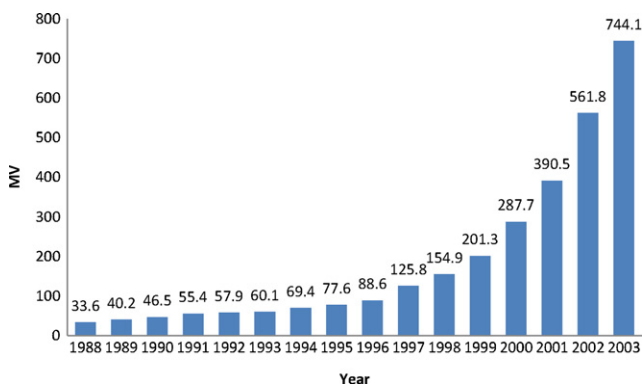


Fig. 15. World PV cell/module production in MWp [47].



Fig. 16. Illustration of BIPV with shading materials [47].

The major issue to encourage the citizens for PV power installations is the financial incentives [4]. Hence, intense research should be made to improve the efficiency and reduce cost of photovoltaic systems.

5.2. Solar electricity for industrial applications

It may be reported that the solar powered systems are reliable and cost-effective. They are largely applied in industrial processes in line with energy sustainability issues. Primary energy consumption released by Shell shows remarkable growth in PV solar electricity by 2030. Fig. 17 shows the sustained growth of global energy consumption [48,49].

Solar electricity is used in many remote and isolated industrial applications such as traffic lights, telecommunication instruments and geographical-position systems (GPS) for the last 15 years. Most of remote installations are off grid or hybrid systems. Off grid systems are independent of public grid and provide electricity to the load solely generated from solar irradiation. The hybrid PV-diesel systems have additional storage batteries or diesel generator. Table 11 is a cost analysis for a 5 kVA Diesel/battery system and a 1.8 kWp PV/5 kVA Diesel/battery system. It was found that hybrid PV-diesel systems are most cost effective.

Storage battery powered by solar energy is used in many telecommunication industries. Telecommunication systems need incessant power which assures continuous operation of the system even during cold or cloudy weather and hazy days when there is no sunlight. Hence need for energy storage with sufficient capacity seems to be necessary which poses some special operational demands in addition to the requirements of batteries operating in conventional ways [50].

Another application of solar electricity in telecommunication industry is solar photovoltaic-powered dc mixing fans used to reduce peak temperature in un-insulated outdoor cabinets con-

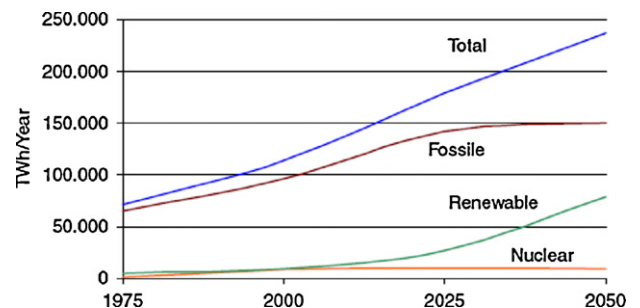


Fig. 17. Global energy consumption [49].

Table 11
Probability increase by adding PV to a diesel-battery system [49].

Electricity generation cost (€/kWh)	Standard lifetime of diesel and battery	Reduced lifetime of battery to 1 year
Diesel (5 kVA) @100% Battery	3.0 €/kWh	5.3 €/kWh
Diesel (5 kVA) @25% Battery PV (1.8 kWp) (@5 kWh/m ² × d)	2.2 €/kWh	3.1 €/kWh

taining telephone equipment. Usually they use thermostatically controlled ac fans. However, operating cost, need for battery reserve and high starting current poses few limitations. The operating cost can be eliminated by solar powered dc fans. The storage batteries are not necessary since the operation of fans is in accordance with solar irradiation and lower starting currents leads the dc fans to longer lifetime [51].

Use of solar energy in agricultural industries can reduce the farm production costs. Poultry industry can use solar photovoltaic systems to generate electricity for bird production running fans and lightings. Conventional poultry producers need huge electrical energy to run their chicken industry. However, solar panels can be installed on the roof spaces available in the poultry houses [4].

5.3. Solar powered water desalination industry

World population growth rate especially in developing countries has brought many concerns such as poverty, pollution, health and environmental problems. Currently, one forth of habitants in the world is deprived of sufficient pure water [42]. Table 12 shows the distribution of world population since 1950 and predictions up to 2050. As observed, the world population is more concentrated in developing countries located in Asia and Africa. Therefore, water desalination technology is seems more necessary in these regions.

Water desalination industry is developed in order to tackle water shortage and overcome the limitations of available water resources. It can provide useful clean water from brackish or sea water. However, conventional desalination methods called supply-side techniques cause huge severe environmental impacts and disturb natural ecosystems. In addition, they require high amount of energy for their operation.

Solar energy can be used to desalinate sea water using small tubs embedded in the life boats so called “solar stills”. Solar stills are suitable for domestic applications, particularly in rural and remote areas, small islands, and big ships with no access to the grid. In this situation, solar energy is economically and technically more competitive than conventional diesel engine powered reverse osmosis alternatives. This method is extremely simple but it needs high initial investment, massive surface, frequent maintenance and sensitivity to weather conditions. Hence its application on large scale production plants is very limited. However, currently most of the low to medium size plants are using this method.

Fig. 18 shows the total water desalination capacity installed worldwide between 1960 and 2005. Based on this figure, there was

Table 12
Distribution of world population since 1950 and predictions up to 2050 (millions) [42].

Year	USA	EU	Africa	Asia	Total
1950	158	296	221	1377	2522
1960	186	316	277	1668	3022
1970	210	341	357	2101	3696
1980	230	356	467	2586	4440
1990	254	365	615	3114	5266
2000	278	376	784	3683	6055
2010	298	376	973	4136	6795
2020	317	371	1187	4545	7502
2030	333	362	1406	4877	8112
2040	343	349	1595	5118	8577
2050	349	332	1766	5268	8909

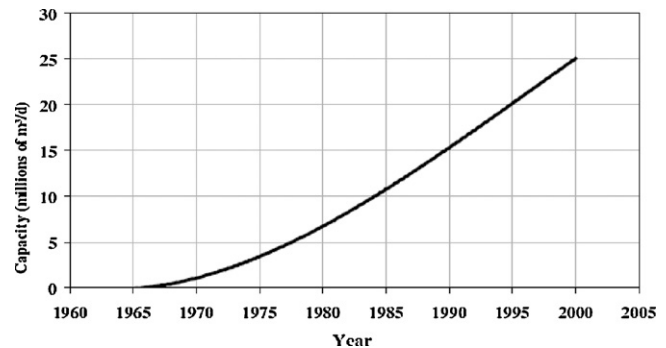


Fig. 18. Global trend in desalination system installation capacity [42].

Table 13
Desalination processes [14].

Phase-change processes	Membrane processes
1. Multistage flash (MSF)	1. → Reverse Osmosis (RO)
2. Multi effect boiling (MEB)	RO without energy recovery
3. Vapor compression (VC)	RO with energy recovery (ER-RO)
4. Freezing	2. → Electro dialysis (ED)
5. Humidification/dehumidification	
6. Solar stills	
Conventional stills	
Special stills	
Wick-type stills	
Multiple-wick-type stills	

an increasing trend in installing desalination plants which will continue in the future. Hence, an investment of \$10 billion is needed to desalinate 5 million m³/d water. Contribution of resources in desalination plants is nearly 65% and 35% for seawater and brackish water, respectively [42].

Common water desalination technologies used in industrial scale are 2 main categories: thermal process or phase-change technologies and membrane technologies or single-phase processes. Table 13 shows the different methods of the two main categories while thermo economic features of the desalination technologies are tabulated in Table 14.

Table 15 shows the possibility of solar thermal usage for MSF and MEE processes. However, solar PV systems can generate electricity for MVC and RO. In addition, they can be integrated to the hybrid RO and MSF systems.

Fig. 19 shows the market share for different water desalination technologies in 2000 [42]. It is shown that MSF and RO are the most common technologies used to desalinate sea and other sources of water.

Table 14
Thermo economic features of the desalination technologies [42].

Technology	MSF	MEE	MVC	RO
Typical average capacity (m ³ /d)	25000	10000	3000	6000
Maximum average capacity (m ³ /d)	50000	20000	5000	10000
Thermal energy consumption (kWh/m ³)	80	60	–	–
Electric energy consumption (kWh/m ³)	4	2	7	5
Equivalent electric energy consumption (kWh/m ³)	15	7	7	5
Cost of plant (\$/m ³ /d)	1300	1200	1000	1000
Production cost (\$/m ³)	1.1	0.8	0.7	0.7

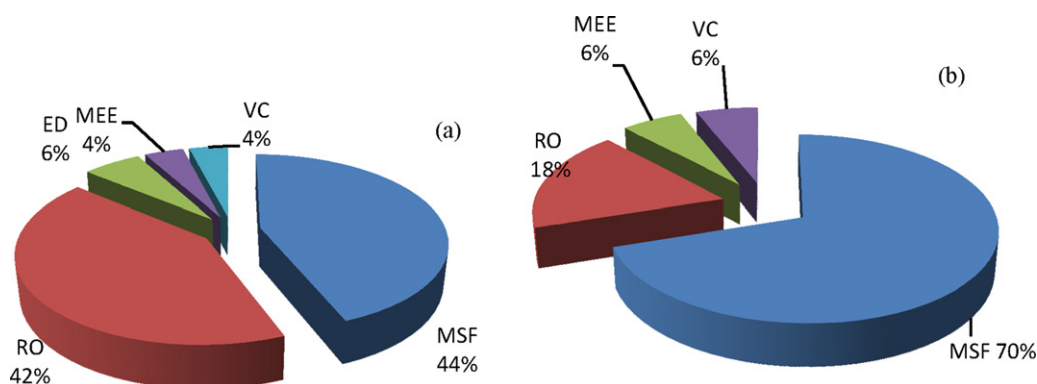


Fig. 19. Desalination technologies market share in 2000: (a) all applications; (b) seawater only [42].

Table 15

Solar energy potential for desalination technologies [42].

Solar energy	MSF	MEE	MVC	RO
Photovoltaic			✓	✓
Solar thermal	✓	✓		
Solar thermal (electric)	✓	✓	✓	✓

Traditional isolated water desalination plants commonly use RO technology supplied by gas or diesel engines. Therefore, solar powered systems are more competitive. Reverse Osmosis and Electro Dialysis desalination systems [45,46] are considered best options for intermittent nature of solar energy source. RO and MF technologies in medium capacity desalination plants with capacity around 1000 m³/d can be coupled with solar thermal and photovoltaic systems, respectively [42].

Solar power systems are reliable substitute to be used as an innovative power source for water desalination plants. It is the most effective and feasible approach for such systems. In addition, they are environmentally friendly and economically competitive compared to traditional methods. The economic outlook for these systems is more considerable when the system is operating in remote regions where there is no access to a public grid. In addition, initial investment, depreciation factor, economic incentives, cost of PV modules and oil price should also be considered [42,52].

6. Conclusions

Applications, developments and forecasts of solar energy used in industries were presented in this paper. It was discussed how the solar energy utilization can improve the quality and quantity of products while reducing the greenhouse gas emissions. It has been found that both solar thermal and PV systems are suitable for various industrial process applications. However, the overall efficiency of the system depends on appropriate integration of systems and proper design of the solar collectors.

Solar energy systems can be considered either as the power supply or applied directly to a process. Large scale solar thermal systems with large collector fields are economically viable due to the usage of stationary collectors. In addition, they need less initial investment cost compared to small plants. Feasibility of integrating solar energy systems into conventional applications depend on industries' energy systems, heating and cooling demand analysis and advantages over existing technologies.

Solar PV systems are reliable substitutes to be considered as an innovative power source in building, processes industries and water desalination systems. The economic outlook for these systems is more viable when the system is operating in remote regions where there is no access to a public grid. In

addition, other technical and economical variables such as wear and tear, initial and running costs, economic incentives, PV module diminishing price rate and oil price raises should not be neglected.

Designers, engineers, architectures, service engineers and material providers must consider solar energy installations as a sustainable energy development. Besides, policies by governments and communities may play a great role to encourage domestic and industrial sector to apply the new technologies.

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